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A review and assessment of the energy utilization efficiency in the Turkish industrial sector using energy and exergy analysis method

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Abstract

Exergy has been seen a key component for a sustainable society, and in the recent years exergy analysis has been widely used in the design, simulation and performance evaluation of thermal and thermo chemical systems. A particular thermo dynamical system is the society of a country, while the energy utilization of a country can be assessed using exergy analysis to gain insights into its efficiency and potential for improvements.

Energy and exergy utilization efficiencies in the Turkish industrial sector (TIS) over the period from 1990 to 2003 are reviewed and evaluated in this study. Energy and exergy analyses are performed for eight industrial modes, namely iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, non-metal industry, other industry, while in the analysis the actual data are used. Sectoral energy and exergy analyses are conducted to study the variations of energy and exergy efficiencies for each subsector throughout the years studied, and these heating and overall energy and exergy efficiencies are compared for the eight subsectors. The chemical and petrochemical subsector, and the iron and steel subsector appear to be the most energy and exergy efficient sectors, respectively. The energy utilization efficiencies for the Turkish overall industrial sector range from 63.45% to 70.11%, while the exergy utilization efficiencies vary from 29.72% to 33.23% in the analyzed years. Exergetic improvement potential for this sector is also determined to be 681 PJ in 2003, with an average increase rate of 9.5% annually for the analyzed years. It may be concluded that the methodology used in this study is practical and useful for analyzing sectoral and subsectoral energy and exergy utilization to determine how efficient energy and exergy are used in the

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sector studied. It is also expected that this study will be helpful in developing highly applicable and productive planning for energy policies.

Keywords: Analysis; Efficiency; Energy; Exergy; Industrial sector; Sustainability; Turkey

Contents

1. Introduction

Known energy sources have been exhausted rapidly nowadays and so, efficient and effective utilization of energy has started to gain a vital importance. For this reason, the collection and evaluation of periodical data concerning industry and other final energy consuming sectors are primary conditions in the determination of targets for the studies on energy saving.

The energy balance is the basic method of a process investigation. It makes the energy analysis possible, points at the needs to improve the process, is the key to optimization and is the basis for developing the exergy balance. Analysis of the energy balance results would disclose the efficiency of energy utilization in particular parts of the process and allow comparing the efficiency and the process parameters with the currently achievable values in the most modern installations. They will also establish the priority of the processes requiring consideration, either because of their excessive energy consumption or because of their particularly low efficiency [1].

The exergy analysis is the modern thermodynamic method used as an advanced tool for engineering process evaluation [2]. Whereas the energy analysis is based on the first law of

Nomenclature

C	specific heat (kJ/kgK)
E	energy (kJ)
$\dot{E}$	energy rate (kW)
ex	specific exergy (kJ/kg)
Ex	exergy (kJ)
$\dot{\mathrm{E}}\mathrm{x}$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
H	enthalpy content of a particular energy carrier (kJ/kg)
$\dot{I}$	rate of irreversibility, rate of exergy consumption (kW)
$\mathrm{I}\dot{\mathrm{P}}$	rate of improvement potential (kW)
ke	specific kinetic energy (kJ/kg)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
pe	potential energy (kJ/kg)
Q	heat transfer (kJ)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kgK)
$\dot{S}$	entropy rate (kW)
W	work (kJ)
$\dot{W}$	rate of work (or power) (kW)

Greek letters

η	energy (first law) efficiency (%)
ε	exergy (second law) efficiency (%)
ψ	flow exergy (kJ/kg)
γ_{f}	fuel exergy grade function
μ_{j_0}	chemical potentials of j components at reference state (kJ/kg)
$\mu_{j_{00}}$	chemical potentials of j components at dead state (kJ/kg)

Indices

0	dead state or reference environment
c	chemical
cp	chemical–petrochemical
e	electrical
f	fuel
h	heating
ic	incompressible
in	input
is	iron–steel
k	location
ke	kinetic energy

o	overall
oi	other industry
p	process
Q	heat
s	stream
w	work

thermodynamics, the exergy analysis is based on both the first and the second laws of thermodynamics. Both analyses utilize also the material balance for the considered system. Analysis and optimization of any physical or chemical process, using the energy and exergy concepts, can provide the two different views of the considered process.

The main purpose of exergy analysis is to discover the causes and quantitatively estimate the magnitude of the imperfection of a thermal or chemical process. Exergy analysis leads to a better understanding of the influence of thermodynamic phenomena on the process effectiveness, comparison of the importance of different thermodynamic factors, and the determination of the most effective ways of improving the process under consideration [2]. A true understanding of exergy and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems are required for the engineer or scientist working in the area of energy systems and the environment. Dincer [3,4] also reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail elsewhere.

Szargut [2], Kotas [5] and Wall [6] have performed most extensive studies in the exergy field. Szargut is the first scientist introducing the cumulative exergy consumption and cumulative degree of perfection for industrial processes and making the distinction between second law efficiency (exergetic efficiency or rational efficiency) and cumulative degree of perfection for industrial processes. However, Kotas has followed a similar approach giving different industrial processes such as sulfuric acid, gas turbine and refrigeration plants. Wall [6] presented the exergy flows for a pulp and paper mill and a steel plant by establishing the energy flows in processes and drawing up the exergy losses.

Exergy is a useful concept, since it is a link between the physical and engineering world and the surrounding environment, and expresses the true efficiency of engineering systems, which makes it a useful concept to find improvements. Therefore, it is used in the design of engineering systems and sectoral energy analysis [7,8].

A brief description of energy and exergy modeling applications is given to provide a better understanding of the differences between the first and second laws of thermodynamics. To attain efficient and effective use of fuels it is essential to consider the quality and quantity of the energy used to achieve a given objective. Table 1 reflects this situation in terms of energy and exergy efficiencies for several processes [7–9]. As is well known, the first law of thermodynamics states that energy is conserved. More specifically, the energy contained in all of the input streams to a process must be accounted for somewhere in the output streams from the same process or accumulated within the system in which the process is occurring. An output stream could be a loss to the atmosphere or other heat sink. The first law efficiencies given in Table 1 represent the energy of the useful streams leaving the process divided by the energy of all streams

Table 1
Energy and exergy efficiencies for some processes for comparison [7–9]

Process	Energy efficiency (%)	Exergy efficiency (%)
Residential heater (fuel)	60	9
Domestic water heater (fuel)	40	2–3
High-pressure steam boiler	90	50
Tobacco dryer (fuel)	40	4
Coal gasification (high heat)	55	46
Petroleum refining	90	10
Steam-heated reboiler	100	40
Blast furnace	76	46

entering. The second law of thermodynamics, on the other hand, contains several implications, including [10]:

(i) the quality, or inherent capacity to cause change, of energy and matter streams is important, and
(ii) the quality of such streams is degraded or destroyed due to irreversibilities in practical processes (and conserved only for the limiting case of ideal, or reversible, processes)

The second law efficiencies listed in Table 1 are based on a ratio of the exergy contained in the products of a process to the exergy in all input streams. First and second law efficiencies are often called *energy* and *exergy efficiencies*, respectively. The exergy efficiencies in Table 1 are lower than the energy efficiencies, usually because the irreversibilities of the process destroy some of the input exergy. The other point that should be highlighted is that high-temperature energy resources, such as fossil fuels, are used for relatively low temperature applications such as residential heating, and domestic hot water. This will make exergy efficiencies much smaller than their respective energy efficiencies. Therefore, it is important to note that high-temperature energy resources should be used for high-temperature applications [10].

The main objective of the present study is to model the energy and exergy flows in a macrosystem and to apply the energy and exergy modeling technique to the TIS over a period from 1990 to 2003. In the energy and exergy analyses, the actual sectoral energy data are used, while energy and exergy efficiencies in Turkey's sectors are studied to see how efficiently energy and exergy were used in these sectors.

2. Methodology used

Establishing and formulating the laws of thermodynamics for thermal systems go back to around the year 1850. The method of exergy analysis has been applied to a wide variety of thermal and thermochemical systems. A particular thermodynamical system is the society, for example, of a country or a region [11]. Recently, there has been increasing interest in using energy and exergy analysis modeling techniques for energy-utilization assessments in order to attain energy saving, and hence financial savings. The energy utilization of a country can be evaluated using exergy analysis to gain insights into its efficiency [8].

Exergy analysis method is a powerful tool, which has been successfully and effectively used for estimating energy utilization efficiencies of countries by various investigators. However, only a few of such analyses are available. The first one was applied by Reistad to the US in 1970, published in 1975 [12], while the most comprehensive one in terms of years appears to be Ayres et al.'s analysis of the US between 1900 and 1998, published in 2003 [13]. Based on the earlier studies conducted on the sectoral energy and exergy analysis of countries by many authors, the approaches used to perform the exergy analyses of countries may be grouped into three types, the first two approaches; namely Reistad's approach and Wall's approach, as denoted by Ertesvag [11] and the last one Scuibba's approach [14,15]. The application of these approaches to various countries has been presented elsewhere in more detail [16].

The first approach considers flows of energy carriers for energy use, while the second one takes into account all types of energy and material flows. Reistad's approach is followed in the analyses of Finland [17], Canada [18], Brazil [19], the Organization for Economic Co-operation and Development (OECD) countries, non-OECD countries, and the world [20], England [21], Saudi Arabia [10,22–24] and, Turkey [8,25–36]. Besides these, the analyses of Sweden [37,38], Ghana [39], Japan [40], Italy [41] and Norway [42] follow Wall's approach. In addition, a new approach Sciubba is introduced to the method of extended-exergy accounting [43,44] and applied to the Italian society 1996 by Milia and Sciubba [43].

3. Theoretical analysis

For a general steady state, steady-flow process, the following balance equations are applied to find the work and heat interactions, the rate of exergy decrease, the rate of irreversibility, the energy and exergy efficiencies [5,16,22].

3.1. Energy and exergy balances

The mass balance equation can be expressed in the rate form as

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}}, \tag{1}$$

where $\dot{m}$ is the mass flow rate, and the subscript *in* stands for inlet and *out* for outlet.

The general energy balance can be expressed as

$$\sum \dot{E}_{\text{in}} = \sum \dot{E}_{\text{out}}, \tag{2}$$

$$\dot{Q} + \sum \dot{m}_{\text{in}} h_{\text{in}} = \dot{W} + \sum \dot{m}_{\text{out}} h_{\text{out}}, \tag{3}$$

where $\dot{E}_{\text{in}}$ is the rate of net energy transfer in, $\dot{E}_{\text{out}}$ is the rate of net energy transfer out by heat, work and mass, $\dot{Q} = \dot{Q}_{\text{net,in}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}$ is the rate of net heat input, $\dot{W} = \dot{W}_{\text{net,out}} = \dot{W}_{\text{out}} - \dot{W}_{\text{in}}$ is the rate of net work output, and h is the specific enthalpy.

Assuming no changes in kinetic and potential energies with any heat or work transfers, the energy balance given in Eq. (3) can be simplified to flow enthalpies only:

$$\sum \dot{m}_{\text{in}} h_{\text{in}} = \sum \dot{m}_{\text{out}} h_{\text{out}}. \tag{4}$$

The general exergy balance can be expressed in the rate form as

$$\sum \dot{\text{E}}\text{x}_{\text{in}} - \sum \dot{\text{E}}\text{x}_{\text{out}} = \sum \dot{\text{E}}\text{x}_{\text{dest}} \tag{5a}$$

or

$$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k-\dot{W}+\sum\dot{m}_{\text{in}}\psi_{\text{in}}-\sum\dot{m}_{\text{out}}\psi_{\text{out}}=\dot{\text{E}}\text{x}_{\text{dest}} \tag{5b}$$

with

$$\psi=(h-h_0)-T_0(s-s_0), \tag{6}$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature T_k at location k, $\dot{W}$ is the work rate, ψ is the flow exergy, s is the specific entropy and the subscript zero indicates properties at the dead state of P_0 and T_0,

The exergy destroyed or the irreversibility may be expressed as follows

$$\dot{I}=\dot{\text{E}}\text{x}_{\text{dest}}=T_0\dot{S}_{\text{gen}} \tag{7}$$

where $\dot{S}_{\text{gen}}$ is the rate of entropy, while the subscript "0" denotes conditions of the reference environment.

The amount of thermal exergy transfer associated with heat transfer Q_r across a system boundary r at constant temperature T_r is [22,31]

$$\text{ex}^Q=[(1-(T_0/T_r))]Q_r. \tag{8}$$

The exergy of an incompressible substance may be written as follows:

$$\text{ex}_{\text{ic}}=C\left(T-T_0-T_0\ \ln\frac{T}{T_0}\right), \tag{9}$$

where C is the specific heat.

3.2. Exergy of a flowing stream of matter

Consider a flowing stream of matter at temperature T, pressure P, chemical composition μ_j, mass m, specific enthalpy h, specific entropy s, and mass fraction x_j of species j. Assume a conceptual environment in an equilibrium state with intensive properties at T_0, P_0 and μ_{j00}, and assume the environment to be large enough such that its intensive properties are negligibly affected by any interactions with the system. With the above considerations, the specific exergy of the flowing stream of matter can be expressed as

$$\Psi=[\text{ke}+\text{pe}+(h-h_0)-T_0(s-s_0)]+\left[\sum_j(\mu_{j0}-\mu_{00})xj\right]. \tag{10}$$

Note that the above equation can be separated into physical and chemical components (assuming ke = 0 and pe = 0). The physical exergy $[(h-h_0)-T_0(s-s_0)]$ is the maximum available work extracted from a flowing stream as it is brought to the environmental state. The chemical exergy $[\sum_j(\mu_{j_0}-\mu_{00})xj]$ is the maximum available work extracted from the stream as it is brought from the environmental state to the dead state.

3.3. The reference environment

Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, acts as an infinite system, and is a sink or source for heat and materials, and experiences only internally reversible processes in which its

intensive properties (that is, temperature T_0, pressure P_0, and chemical potentials μ_{j00} for each of the j components) remain constant. With minor exceptions, Gaggioli and Petit's model [45] is used as a reference environment in which $T_0 = 10\,°C$, $P_0 = 1\,atm$, the chemical composition is taken to be air saturated with water vapor, and the following condensed phases are used at 25 °C and 1 atm: water (H_2O), gypsum ($CaSO_4$, $2H_2O$), and limestone ($CaCO_3$). It is noted that, following Gaggioli and Petit [45], gypsum and limestone are taken to be part of the reference environment so as to provide nonreactive, deadstate chemical forms for the elements such as sulfur and calcium.

For computational ease, the temperature T_0 and pressure P_0 of the environment are often taken as standard-state values, such as 1 atm and 25 °C. However, these properties may be specified differently depending on the application. T_0 and P_0 might be taken as the average ambient temperature and pressure, respectively, for the location at which the system under consideration operates. Or, if the system uses atmospheric air, T_0 might be specified as the average air temperature. If both air and water from the natural surroundings are used, T_0 would be specified as the lower of the average temperatures for air and water [46].

3.4. *Energy and exergy efficiencies*

Different ways of formulating exergetic efficiency proposed in the literature have been given in detail elsewhere [47,48]. The exergy efficiency expresses all exergy input as used exergy, and all exergy output as utilized exergy. Therefore, the exergy efficiency ε_1 becomes

$$\varepsilon_1 = \frac{\dot{E}x_{out}}{\dot{E}x_{in}}. \tag{11}$$

Often, there is a part of the output exergy that is unused, i.e. an exergy wasted, $\dot{E}x_{waste}$ to the environment. In this case, exergy efficiency may be written as follows [48]:

$$\varepsilon_2 = \frac{\dot{E}x_{out} - \dot{E}x_{waste}}{\dot{E}x_{in}}. \tag{12}$$

The rational efficiency is defined by Kotas and Cornelissen [5,47] as the ratio of the desired exergy output to the exergy used, namely

$$\varepsilon_3 = \frac{\dot{E}x_{desired,output}}{\dot{E}x_{used}}, \tag{13a}$$

where $\dot{E}x_{desired,output}$ is all exergy transfer rate from the system, which must be regarded as constituting the desired output, plus any by-product that is produced by the system, while $\dot{E}x_{used}$ is the required exergy input rate for the process to be performed. The exergy efficiency given in Eq. (13a) may also be expressed as follows [48]:

$$\varepsilon_3 = \frac{\text{Desired exergetic effect}}{\text{Exergy used to drive the process}} = \frac{\text{product}}{\text{fuel}}. \tag{13b}$$

To define the exergetic efficiency both a *product* and a *fuel* for the system being analyzed are identified. The product represents the desired result of the system (power, steam, some combination of power and steam, etc.). Accordingly, the definition of the product must be consistent with the purpose of purchasing and using the system. The fuel represents the resources expended to generate the product and is not necessarily restricted to being an

actual fuel such as a natural gas, oil, or coal. Both the product and the fuel are expressed in terms of exergy [49].

Energy (first law) and exergy (second law) utilization efficiencies in %, η and ε_1, can also be defined as follows, respectively.

$$\eta = (\text{Energy in products/total energy input})\ 100, \tag{14}$$

$$\varepsilon_1 = (\text{Exergy in products/total exergy input})\ 100. \tag{15}$$

The energy and exergy efficiencies for heating, work production, and kinetic energy production processes are stated as below [10,22].

Electric and fossil fuel heating processes are taken to generate product heat Q_p at a constant temperature T_p either from electrical energy W_e or fuel mass m_f. The efficiencies for electrical heating and fuel heating are:

$$\eta_{e,h} = Q_p/W_e \quad \text{and} \quad \eta_{f,h} = Q_p/m_f H_f, \tag{16}$$

$$\varepsilon_{1e,h} = \text{Ex}^{Q_p}/\text{Ex}^{W_e} \quad \text{and} \quad \varepsilon_{1f,h} = \text{Ex}^{Q_p}/m_f\varepsilon_f \tag{17}$$

and hence

$$\varepsilon_{1e,h} = [(1-(T_0/T_p))Q_p]/(W_e) \quad \text{and} \quad \varepsilon_{1f,h} = [(1-(T_0/T_p))Q_p]/(m_f\gamma_f H_f), \tag{18}$$

$$\varepsilon_{1e,h} = [(1-(T_0/T_p))]\eta_{e,h} \quad \text{and} \quad \varepsilon_{1f,h} = [(1-(T_0/T_p))]\eta_{f,h} \tag{19}$$

where double subscripts indicate the processes in which the quantity represented by the first subscript is produced by the quantity represented by the second; e.g., the subscripts h, e, f, means heating electricity with fuel.

Electric and fossil–fuel work production processes produces shaft work W. The efficiencies for shaft work production from electric and fossil fuels are as follows:

$$\eta_{e,w} = W/W_e \quad \text{and} \quad \eta_{f,w} = W/m_f H_f, \tag{20}$$

$$\varepsilon_{1e,w} = \text{Ex}^W/\text{Ex}^{W_e} = W/W_e = \eta_{e,w} \quad \text{and}$$
$$\varepsilon_{1f,w} = \text{Ex}^W/m_f H_f = W/(m_f\gamma_f H_f) = \eta_{f,w}/\gamma_f. \tag{21}$$

The efficiencies for the fossil fuel-driven kinetic energy production processes, which occur in some devices in the transportation sector and which produces a change in kinetic energy Δke in a stream of matter m_s, are as follows:

$$\eta_{f,ke} = m_s\Delta \text{ke}_s/m_f H_f, \tag{22}$$

$$\varepsilon_{1f,ke} = m_s\Delta \text{ke}_s/m_f\varepsilon_f = m_s\Delta \text{ke}_s/(m_f\gamma_f H_f) = \eta_{f,ke}/\gamma_{f,ke}. \tag{23}$$

3.5. Improvement potential

Van Gool [50] has also noted that maximum improvement in the exergy efficiency for a process or system is obviously achieved when the exergy loss or irreversibility ($\dot{\text{Ex}}_{in} - \dot{\text{Ex}}_{out}$) is minimized. Consequently, he suggested that it is useful to employ the concept of an exergetic "*improvement potential*" when analyzing different

processes or sectors of the economy give this improvement potential in a rate form, denoted IP [21].

$$\dot{IP} = (1 - \varepsilon)(\dot{E}x_{in} - \dot{E}x_{out}). \quad (24)$$

4. An outlook on Turkey's industrial sector

Turkey, with a population of 70,778 million on 800,000 km^2 of land, is located between 35°50′ and 42°06′ north latitudes and 25°40′ and 44°48′ east longitudes. Most of Turkey is in Asia. The far northwestern part of the country is in Europe and is separated from the rest of the country by the Dardanelles and Bospherous Straits and the Sea of Marmara. Population growth in Turkey has been recording high rates, as have trends around the world, growing by an average of 1.8%/annum over the period 1990–2003, to rise from 56,473 million in 1990 to 70,778 million in 2003 [30,34,51–54].

The industrial sector of Turkey is also complex and composed of many sub sectors. In order to simplify the analysis of energy and exergy efficiencies for this sector, energy consumption flow is analyzed for all the subsectors, namely iron–steel, chemical–petro-chemical, petrochemical–feedstock, cement, fertilizer, sugar, non-metal industry and other industry, to represent the entire sector that consumed more than half of the total energy consumption in this country.

The methodology used in this study for analyzing energy and exergy efficiencies in the industrial sector is similar to that of Rosen and Dincer [8], who used Reistad's approach [12] with several minor differences. The relations used in the analysis, such as energy and exergy efficiencies of some typical processes as well as the whole sector and exergy improvement potential, may be obtained from Refs. [21,32].

The values of total energy and exergy input to the whole of Turkey as well as the TIS are determined using the data obtained from various sources [51–54]. The structure of Turkey's total, industrial and its subsectors energy and exergy inputs from 1990 to 2003 is listed in Table 2, while some characteristics of fuels used in the TIS are given in Table 3 [10,12,16]. As can be seen in Table 2, total energy and exergy inputs to the whole of Turkey were 2009.3 PJ and 2017.8 PJ in 1990, respectively. However, they were determined to be 3496.15 and 3438.66 PJ in 2003, respectively. Of total energy input, 48.08% and 31.20% were produced in 1990 and 2003, respectively, while the rest was met by imports.

Fig. 1 illustrates energy and exergy flows in a macrosystem for Turkey's whole and TIS. In 1990, of Turkey's total end-use energy, 35% was used by the industrial sector, followed by the residential-commercial sector at 37%, the transportation sector at 21%, the agricultural sector at 4.7%, and the non energy (out of energy) use at 2.3% [30]. However, in 2003, of Turkey's total end-use energy, 42% was used by the industrial sector, followed by the residential–commercial sector at 31%, the transportation sector at 19%, the agricultural sector at 4.8%, and the non energy (out of energy) use at 3.2% [53,54].

5. Result and discussion

The methodology presented in the previous section is applied to the TIS for energy and exergy use.

Table 2
Energy and exergy consumption data for the Turkish industrial sector from 1990 to 2003

Year		Turkey total (PJ)	Industrial		Iron–steel		Chemical-petrochemical		Petrochemical-feedstock		Fertilizer		Cement		Sugar		Non iron metals		Other industry	
			F[a] (PJ)	E[b] (PJ)	F (PJ)	E (PJ)	F (PJ)	E (PJ)	F (PJ)	E (PJ)	F (PJ)	E (PJ)	F (PJ)	E (PJ)	F (PJ)	E (PJ)	F (PJ)	E (PJ)	F (PJ)	E (PJ)
1990	Energy	2009.30	509.31	100.88	108.57	17.40	35.17	14.53	61.75	0.00	31.66	4.14	81.11	14.35	27.49	1.37	13.90	9.18	149.61	39.91
	Exergy	2017.81	514.97	100.88	112.45	17.40	35.09	14.53	61.14	0.00	30.35	4.14	83.12	14.35	28.28	1.37	13.90	9.18	150.59	39.91
1991	Energy	2201.36	541.90	97.26	111.99	17.96	36.77	11.59	54.03	0.00	29.77	3.59	91.57	15.30	27.62	1.44	13.41	8.71	176.72	38.66
	Exergy	2207.67	547.28	97.26	115.68	17.96	35.92	11.59	53.49	0.00	28.45	3.59	93.40	15.30	28.45	1.44	13.37	8.71	178.50	38.66
1992	Energy	2325.30	542.25	107.90	112.43	21.50	38.46	12.58	56.44	0.00	37.54	1.48	78.19	17.01	22.62	1.44	13.92	9.46	182.67	44.42
	Exergy	2330.08	545.20	107.90	115.94	21.50	37.57	12.58	55.88	0.00	35.64	1.48	80.03	17.01	23.24	1.44	13.89	9.46	183.05	44.42
1993	Energy	2478.67	569.76	117.15	110.58	24.21	43.08	17.24	60.88	0.00	33.72	1.59	77.48	17.61	21.01	1.98	12.68	9.61	210.35	44.91
	Exergy	2478.63	571.66	117.15	114.20	24.21	42.15	17.24	60.27	0.00	31.34	1.59	79.75	17.61	21.52	1.98	12.66	9.61	209.77	44.91
1994	Energy	2461.38	524.73	116.72	107.86	23.45	38.16	14.88	64.08	0.00	28.55	1.37	87.09	15.34	15.58	1.08	16.61	7.55	166.79	53.06
	Exergy	2461.85	527.14	116.72	111.51	23.45	37.52	14.88	63.44	0.00	26.59	1.37	90.26	15.34	15.94	1.08	16.63	7.55	165.23	53.06
1995	Energy	2343.08	601.41	130.64	111.61	25.00	42.00	15.73	69.43	0.00	36.15	1.37	80.59	10.36	17.39	1.28	24.07	7.79	220.56	69.10
	Exergy	2350.28	601.91	130.64	115.56	25.00	41.18	15.73	68.74	0.00	33.96	1.37	83.55	10.36	17.65	1.28	23.70	7.79	217.92	69.10
1996	Energy	2906.74	691.65	140.06	123.46	28.63	40.30	18.85	63.33	0.00	36.87	1.45	92.72	9.77	20.77	1.22	19.67	7.04	291.94	73.11
	Exergy	2900.94	695.76	140.06	127.86	28.63	39.63	18.85	62.70	0.00	34.51	1.45	96.32	9.77	21.16	1.22	19.18	7.04	291.93	73.11
1997	Energy	3051.40	752.19	157.50	123.16	31.14	46.28	22.24	64.04	0.00	33.39	2.98	84.99	16.36	23.03	1.22	16.93	7.04	360.32	76.52
	Exergy	3040.73	755.76	157.50	127.65	31.14	45.17	22.24	63.40	0.00	31.07	2.98	88.04	16.36	23.28	1.22	16.68	7.04	360.43	76.52
1998	Energy	3121.31	731.31	166.50	111.67	31.29	36.12	23.80	71.63	0.00	25.00	2.69	73.54	10.13	26.06	1.22	14.87	7.04	372.49	90.34
	Exergy	3108.42	735.88	166.50	115.67	31.29	35.84	23.80	70.91	0.00	23.51	2.69	76.58	10.13	26.74	1.22	14.84	7.04	371.86	90.34
1999	Energy	3117.38	658.63	168.67	109.58	27.81	46.00	22.10	63.38	0.00	7.83	1.29	93.48	8.93	25.42	1.22	25.69	7.04	287.25	100.29
	Exergy	3094.87	662.48	168.67	113.68	27.81	44.94	22.10	62.74	0.00	7.41	1.29	97.15	8.93	26.03	1.22	24.82	7.04	285.71	100.29
2000	Energy	3390.08	810.50	176.08	115.26	30.18	47.01	22.94	62.85	0.00	9.19	1.80	85.73	14.37	20.68	1.22	27.44	7.04	442.23	98.54
	Exergy	3361.89	818.01	176.08	119.61	30.18	45.90	22.94	62.22	0.00	8.82	1.80	89.09	14.37	21.25	1.22	26.77	7.04	444.24	98.54
2001	Energy	3199.04	692.82	221.45	107.33	30.11	49.45	20.00	62.81	0.00	63.15	1.75	80.45	11.59	46.82	1.22	27.82	7.04	292.35	149.74
	Exergy	3160.94	693.90	221.45	111.35	30.11	48.14	20.00	62.18	0.00	62.53	1.75	83.67	11.59	47.01	1.22	27.12	7.04	289.21	149.74
2002	Energy	3274.53	841.67	173.57	101.78	29.81	48.81	7.64	66.63	0.00	23.00	1.84	106.66	11.81	46.78	1.22	32.73	9.17	443.10	112.09
	Exergy	3229.66	842.36	173.57	105.60	29.81	47.62	7.64	65.96	0.00	21.48	1.84	110.76	11.81	46.96	1.22	31.69	9.17	440.70	112.09
2003	Energy	3496.15	929.63	186.37	108.96	31.60	51.11	7.64	59.56	0.00	21.94	1.79	89.41	12.36	30.51	1.22	30.37	9.17	537.80	122.58
	Exergy	3438.66	929.77	186.37	113.21	31.60	49.77	7.64	58.96	0.00	20.51	1.79	92.94	12.36	30.74	1.22	29.20	9.17	534.49	122.58

[a] Fuel.
[b] Electrical.

Table 3
Quality factor of energy carriers and flows used industrial sector [10,12,16]

Energy carriers	Enthalpy (kJ/kg)	Chemical exergy (kJ/kg)	Quality factor
Natural gas	55448	51702	0.92
Hard coal	25552	26319	1.03
Fuel oil	47405	47101	0.99
LPG	45460	45005	0.99
Geothermal	36006.48	10441.87	0.29
Electricity	3600.6	3600.6	1.00
Solar	36006.48	33485.58	0.93
Mechanical energy			1.00
Steam (600 °C)			0.60
District heating (90 °C)			0.2–0.3
Space heating (20 °C)			0–0.2
Earth			0

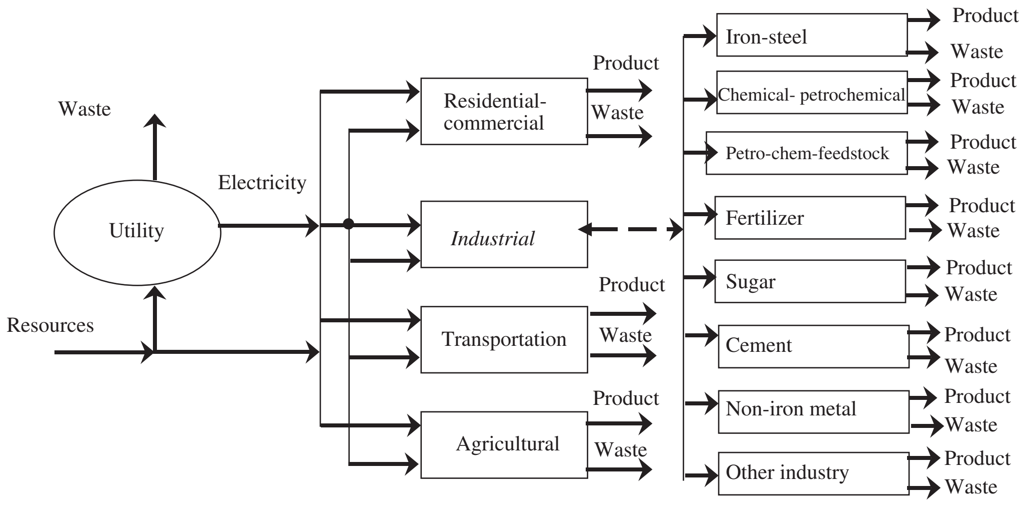

Fig. 1. An illustrative presentation of the energy flows in a macrosystem and the Turkish industrial sector.

5.1. *Analysis of the Turkish industrial sector*

This section presents the analysis of the energy utilization data of the industrial sector in Turkey.

5.1.1. *Application of the methodology*

The TIS is composed of many industries, but the eight most significant industries are identified as iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, non-metal industry, other industries. In order to simplify the analysis of energy and exergy efficiencies for this complex sector, energy consumption patterns are analyzed, and the eight most significant industries (in which the total energy consumption accounts for more than 95% of the total energy used in this sector) are chosen to represent the entire sector.

Table 4
Process heating temperatures and efficiencies for the industrial sector [10,22,55]

Category T_p	Heating energy efficiency (%)		
	T_p (°C)	Electrical $\eta_{e,h}$	Fuel $\eta_{f,h}$
Low	<121	100	65.5
Medium	121–399	90	60
High	>399	70	50

In the TIS, the energy used to generate heat for production processes accounts for 82% of the total energy consumption, with mechanical drives, lighting, air-conditioning accounting for 18%. In the present study, it is decided to analyze the heating and mechanical end uses only. This simplification is considered valid since heating and mechanical processes account for 95% of the energy consumption in the industrial sector.

Assumptions and simplifications made for the heating and mechanical processes are as follows: heating processes for each industry are grouped into low, medium, and high temperature categories as shown in Table 4 [10,22,55]. The temperature ranges given in Table 4 are based on the work of Brown et al. [55] and Dincer et al. [10,22]. The efficiencies for the medium- and high-temperature categories are obtained from Reistad [12]. All mechanical drives are assumed to be 90% energy efficient [55,56].

Three steps are used to derive the overall efficiency of the sector.

(1) Energy and exergy efficiencies are obtained for process heating for each of the T_p categories.
(2) Mean heating energy and exergy efficiencies for the eight industries are calculated using a two-step procedure:
   (i) weighted mean efficiencies for electrical heating and fuel heating are evaluated for each industry.
   (ii) weighted mean efficiencies for all heating processes in each industry are evaluated with these values, using weighting factors as the ratio of the industry energy consumption (electrical or fuel) to the total consumption of both electrical and fuel energy.
(3) Weighted mean overall (that is, heating and mechanical drive) efficiencies for each industry are evaluated using the weighting factor as the fractions of the total sectoral energy input for both heating and mechanical drives.

In the determination of sector efficiencies, weighted means for the weighted mean overall energy and exergy efficiencies for the major industries in the TIS are obtained, using the weighting factor as the fraction of the total industrial energy demand supplied to each industry.

The efficiency calculations for a cement industry are shown in detail in following subsection.

5.1.2. Process heat efficiency calculations for the product heat temperature categories in each industry

Product heat data for each industry are separated into the categories defined in Table 4. The resulting breakdown is shown in Table 5, with the percentage of heat in each category supplied by electricity and fossil fuels [10,22,55].

Table 5
Process heating data and energy–exergy efficiency data for all categories of product heat temperature (T_p) in the industrial sector [10,55]

Industry	T_p range	Breakdown of energy used for each T_p (%)[a]			Breakdown of energy and exergy efficiencies for each T_p category, by type			
					Electrical heating		Fuel heating	
		Mean T_p (°C)	Electricity	Fuel	$\eta_{h,e}$	$\varepsilon_{1h,e}$	$\eta_{h,f}$	$\varepsilon_{1h,f}$
Iron and steel	Low	45	4.2	0	100.00	6.29	65.00	4.09
	Medium		0	0	90.00	—	60.00	—
	High	983	95.8	100	70.00	53.39	50.00	38.14
Chemical and petrochemical	Low	42	62.5	0	100.00	5.40	65.00	3.51
	Medium	141	37.5	100	90.00	25.22	60.00	16.81
	High	494	0	0	70.00	42.80	50.00	30.57
Petrochemical–Feedstock	Low	57	0	0	100.00	9.70	65.00	6.30
	Medium	227	0	0	90.00	36.36	60.00	24.24
	High	494	0	100	70.00	42.80	50.00	30.57
Fertilizer	Low	57	10	30	100.00	9.70	65.00	6.30
	Medium	350	80	30	90.00	46.95	60.00	31.30
	High	900	10	40	70.00	52.22	50.00	37.30
Cement	Low	42	91.7	0.9	100.00	5.39	65.00	3.50
	Medium	141	0	9	90.00	25.22	60.00	16.81
	High	586	8.3	90.1	70.00	45.71	50.00	32.65
Sugar	Low	83	100	59	100.00	16.29	65.00	10.59
	Medium	315	0	9	90.00	44.39	60.00	29.59
	High	400	0	32	70.00	39.00	50.00	27.86
Non-iron metals	Low	61	10	13.8	100.00	10.78	65.00	7.01
	Medium	132	9.4	22.6	90.00	23.78	60.00	15.85
	High	401	80.4	63.6	70.00	39.05	50.00	27.89
Other ındustry	Low	57	10.6	13.8	100.00	9.70	65.00	6.30
	Medium	132	89.4	86.2	90.00	23.78	60.00	15.85
	High	400	0.1	0.1	70.00	39.00	50.00	27.86

Electrical process heat calculations. In the cement industry, electric heating is used to supply low and medium categories of heat as shown in Table 5. Based on the table data and Eq. (16), the energy efficiency for this end use is

$$\eta_{\mathrm{e,h}} = Q_{\mathrm{p}}/W_{\mathrm{e}} = 1.$$

Using Eq. (18) with $T_0 = 298\,\mathrm{K}$, the exergy efficiencies for the two categories are:
Low: $T_{\mathrm{p}} = 315\,\mathrm{K}$.

$$\varepsilon_{\mathrm{1e,h}} = [(1 - (T_0/T_{\mathrm{p}}))Q_{\mathrm{p}}]/W_{\mathrm{e}} = [1 - (298/315)] \times 1 = 0.053 \text{ (or 5.39\%)}$$

Medium: $T_{\mathrm{p}} = 414\,\mathrm{K}$

$$\varepsilon_{\mathrm{1e,h}} = [(1 - T_0/T_{\mathrm{p}})Q_{\mathrm{p}}]/W_{\mathrm{e}} = [1 - (298/414)] \times 0.9 = 0.2522 \text{ (or 25.22\%)}$$

High: $T_{\mathrm{p}} = 859\,\mathrm{K}$

$$\varepsilon_{\mathrm{1e,h}} = [(1 - (T_0/T_{\mathrm{p}}))Q_{\mathrm{p}}]/W_{\mathrm{e}} = [1 - (298/859)] \times 0.7 = 0.4571 \text{ (or 45.71\%)}.$$

Similarly, the exergy efficiencies for the other sub-sectors of process heating can be found using the same method of calculations. The results are presented in Table 5.

Fossil fuel process heat calculations. The cement industry requires fossil fuel heating at all ranges of temperatures as given in Table 5. The energy efficiency for the low temperature heating process is found using Eq. (16) and data from Table 5:

$$\eta_{\mathrm{f,h}} = Q_{\mathrm{p}}/m_{\mathrm{f}}H_{\mathrm{f}} = 0.65 \text{ (or 65\%)}.$$

Similarly, the energy efficiency for the medium-temperature and high-temperature heating processes is found to be equal to 60 and 50%, respectively.

Using Eq. (18) and a reference temperature (T_0) equal to 298 K and a process temperature (T_{p}) of 315 K from Table 5, the corresponding exergy efficiency for low temperature heating is found as follows:

$$\varepsilon_{\mathrm{1f,h}} = [(1 - (298/315))Q_{\mathrm{p}}]/(m_{\mathrm{f}}\gamma_{\mathrm{f}}H_{\mathrm{f}}).$$

Assuming $\gamma_{\mathrm{f}} = 1$, we combine Eqs. (16) and (18) to obtain the exergy efficiency for low-temperature heating as

$$\varepsilon_{\mathrm{1f,h}} = [(1 - (298/315)] \times 0.65 = 0.035 \text{ (or 3.50\%)}.$$

Similarly, the exergy efficiencies for the medium and high temperature heating processes can be found to be equal to 16.81% and 32.65%, respectively.

Similarly, the exergy efficiencies for fuel and electric process heating for each industry have been evaluated using the same method of calculations. The results are presented in Table 5.

5.1.3. Mean process heating efficiencies for all temperature categories in each industry of the industrial sector

Prior to obtaining the overall energy and exergy efficiencies for the industrial sector, the overall heating efficiencies for each industry are evaluated. The methodology is illustrated in detail for the cement industry [10,22].

Mean heating energy and exergy efficiencies. A combined efficiency for the three temperature categories for electric and fossil fuel processes must be calculated in order to obtain an average for overall heating in a given industry.

Using the energy fractions data from Table 5 and the energy and exergy efficiencies presented in Table 5, an average heating efficiency for the cement industry can be calculated. Because electrical heating is used in two categories in the cement industry, the energy efficiency for electrical heating ($\eta_{h.e}$) can be evaluated as follows:

$$\eta_{h.e} = (\text{fraction in category}) \times (\text{energy efficiency}),$$

$$\eta_{h.e} = (91.7 \times 100) + (8.3 \times 70) \Rightarrow \eta_{h.e} = 97.51\%.$$

Similarly, the exergy efficiency ($\varepsilon_{1h,e}$) is calculated as follows:

$$\varepsilon_{1h,e} = (91.7 \times 5.39) + (8.3 \times 45.71) \Rightarrow d\varepsilon_{1h,e} = 8.74\%.$$

Fossil fuel heating in the cement industry is used in all temperature categories. Using the data given in Table 4, the energy and exergy efficiencies for fuel heating for the year 2003 are found as follows:

$$\eta_{h.f} = (0.9 \times 65) + (9 \times 60) + (90.1 \times 50) \Rightarrow \eta_{h.f} = 51.04\%,$$

$$\varepsilon_{1h.f} = (0.9 \times 3.50) + (9 \times 16.81) + (90.1 \times 32.65) \Rightarrow \varepsilon_{1h,f} = 30.96\%.$$

Using the data from Table 2, the fraction of total energy utilized by the cement industry for electrical (E_e) and fossil fuel (E_f) is found for the year 2003 as follows:

For electrical energy:

$$E_e = \frac{\text{electrical energy}}{\text{total energy}} = \frac{12.36}{89.41 + 12.36} = 0.121 \text{ (or } 12.1\%).$$

For fossil fuel energy:

$$E_f = 1.00 - 0.121 = 0.879 \text{ (or 87.9 percent)}.$$

For electrical exergy:

$$E_e = \frac{\text{electrical exergy}}{\text{total exergy}} = \frac{12.36}{92.94 + 12.36} = 0.085 \text{ (or } 8.51\%).$$

For fossil fuel exergy:

$$E_f = 1.00 - 0.085 = 0.915 \text{ (or } 91.5\%).$$

Using the calculated energy efficiencies $\eta_{h.e}$ and $\eta_{h.f}$, and the fraction of electrical (E_e) and fossil fuel energy (E_f) used by the cement industry, the overall mean energy and exergy efficiencies for heating can be calculated as

$$\eta_h = (0.121 \times 97.51) + (0.879 \times 51.04) \Rightarrow \eta_h = 56.68\%,$$

$$\varepsilon_{1h} = (0.085 \times 8.74) + (0.915 \times 30.96) \Rightarrow \varepsilon_{1h} = 28.36\%.$$

Following the same methodology, mean heating energy and exergy efficiencies for the other seven industries considered are determined as indicated in Table 6. The graphical representation of the mean heating energy and exergy efficiencies for the year 2003 is shown in Fig. 2. Overall energy ($\eta_{h,o}$) and exergy ($\varepsilon_{1h,o}$) efficiencies of the industrial sector

Table 6
Process heating efficiency data for the industrial sector in Turkey from 1990 to 2003

Year	Total industrial		Iron–steel		Chemical–petrochemical		Petrochemical–feedstock		Fertilizer		Cement		Sugar		Non-iron metals		Other industry	
	η (%)	ε_1 (%)	η (%)	ε_1 (%)	η (%)	ε_1 (%)	η (%)	ε_1 (%)	η (%)	ε_1 (%)	η (%)	ε_1 (%)	η (%)	ε_1 (%)	η (%)	ε_1 (%)	η (%)	ε_1 (%)
1990	60.53	25.55	52.94	39.92	70.60	15.65	50.00	30.57	61.15	28.31	58.02	27.69	61.66	17.76	62.45	27.23	67.14	16.16
1991	60.28	25.19	52.94	39.92	68.69	15.84	50.00	30.57	60.89	28.17	57.69	27.84	61.74	17.75	62.37	27.19	66.19	15.91
1992	60.81	25.08	53.41	40.21	68.94	15.81	50.00	30.57	58.69	26.90	59.34	27.07	62.16	17.74	62.59	27.32	66.68	16.05
1993	61.18	24.63	53.82	40.46	70.36	15.66	50.00	30.57	58.92	27.05	59.64	26.95	63.21	17.70	63.13	27.65	66.09	15.90
1994	60.19	24.98	53.80	40.44	70.17	15.68	50.00	30.57	58.94	27.06	57.99	27.74	62.36	17.73	60.71	26.17	68.07	16.42
1995	61.39	24.79	53.89	40.50	69.88	15.71	50.00	30.57	58.65	26.88	56.33	28.51	62.52	17.72	59.32	25.36	67.99	16.40
1996	61.20	24.11	54.00	40.57	71.55	15.53	50.00	30.57	58.69	26.91	55.47	28.92	61.99	17.74	59.71	25.62	66.83	16.09
1997	62.03	23.27	54.29	40.74	71.77	15.50	50.00	30.57	60.08	27.74	58.54	27.48	61.78	17.75	60.32	25.97	66.06	15.89
1998	62.55	23.01	54.65	40.96	74.40	15.22	50.00	30.57	60.56	28.00	56.66	28.37	61.55	17.76	60.89	26.28	66.67	16.05
1999	62.23	23.73	54.30	40.75	71.76	15.50	50.00	30.57	61.97	28.81	55.09	29.10	61.60	17.76	42.65	25.03	68.60	16.55
2000	62.64	22.29	54.41	40.81	71.89	15.48	50.00	30.57	62.65	29.17	57.71	27.88	62.00	17.74	58.49	24.87	66.28	15.94
2001	67.05	24.12	54.66	40.96	70.44	15.64	50.00	30.57	58.35	26.68	56.89	28.26	60.77	17.79	58.45	24.85	71.03	17.18
2002	63.83	23.07	54.82	41.06	64.91	16.26	50.00	30.57	59.83	27.58	55.67	28.83	60.77	17.79	58.80	25.08	66.88	16.11
2003	62.54	21.79	54.78	41.03	64.71	16.28	50.00	30.57	59.88	27.61	56.68	28.36	61.30	17.77	59.06	25.26	66.38	15.98

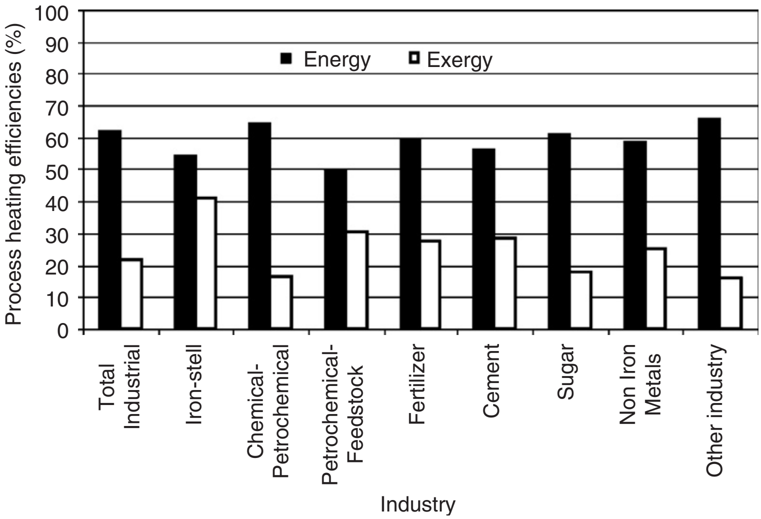

Fig. 2. Mean heating energy and exergy efficiencies of the industrial sector and its subsectors in 2003.

are calculated by the following equations:

$$\eta_{h,o} = [(a_{1s} * \eta_{h,1s}) + (a_{pc} * \eta_{h,pc}) + (a_c * \eta_{h,c}) + \cdots + (a_{o1} * \eta_{h,o1})]/E_i, \tag{25a}$$

$$\varepsilon_{1h,o} = [(a_{1s} * \varepsilon_{1h,1s}) + (a_{pc} * \varepsilon_{1h,pc}) + (a_c * \varepsilon_{1h,c}) + \cdots + (a_{o1} * \varepsilon_{1h,o1})]/E_{xi}, \tag{25b}$$

where a denote the share of the relevant utilization subsector in the total for electrical and direct fuel uses in percent. With corresponding process heating energy (η_h) and exergy (ε_{1h}) efficiency values and the total energy consumption from Tables 2 and 6, respectively, an overall average heating energy ($\eta_{h,o}$) and exergy efficiencies ($\varepsilon_{1h.o}$) are obtained for the 14 years between 1990 and 2003. Substituting the relevant numerical values into Eqs. (25a) and (25b), we obtained $\eta_{h,o} = 62.54\%$, and $\varepsilon_{1h,o} = 21.79\%$ in 2003 for overall heating industrial sector. These are graphically represented in Fig. 3 for the analyzed years.

5.1.4. Overall efficiencies for the industrial sector

Overall energy and exergy efficiencies for the industrial sector are obtained using the process heating efficiencies previously calculated and the mechanical drive efficiency, which is assumed to be 90%. Also, for calculating the overall efficiency, the total industrial energy consumption for each industry is used (Table 2).

In addition, including mechanical drives, substituting the relevant numerical values into Eqs. (25a) and (25b), we calculated $\eta_o = 65.73\%$, and $\varepsilon_{1,o} = 29.72\%$ in 2003 for overall TIS and these values are shown in Fig. 4 for the analyzed years.

5.2. Estimation of the exergetic improvement potential in the TIS

Using Eq. (24), Van Gool's exergetic improvement potential [50] was studied for the Turkish transportation sector by Utlu and Hepbasli [34]. Here, over the period from 1990

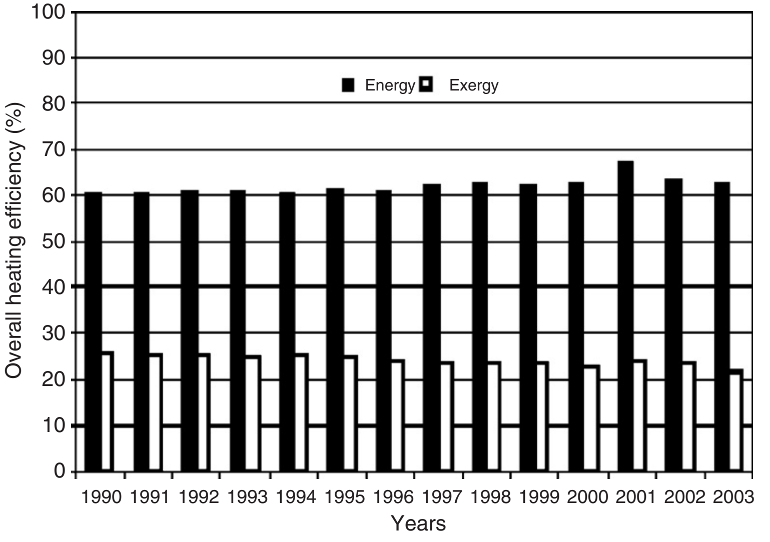

Fig. 3. Overall heating energy and exergy efficiencies of the Turkish industrial sector over the period from 1990 to 2003.

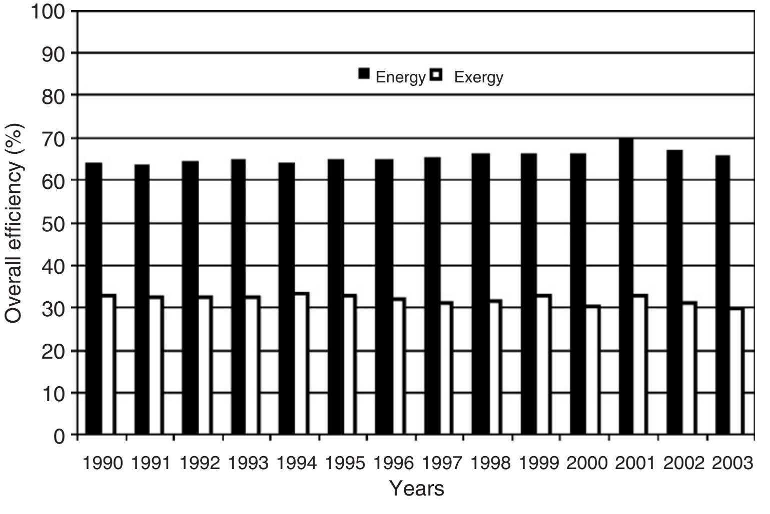

Fig. 4. Overall energy and exergy efficiencies of the Turkish industrial sector over the period from 1990 to 2003.

to 2003, exergetic improvement potential was determined for the TIS and is illustrated in Fig. 5, where exergy input and output values are also plotted. As can be seen from this figure, this potential increases from about 341 PJ in 1990 to some 681 PJ in 2003, with an average increase rate of 9.5% annually.

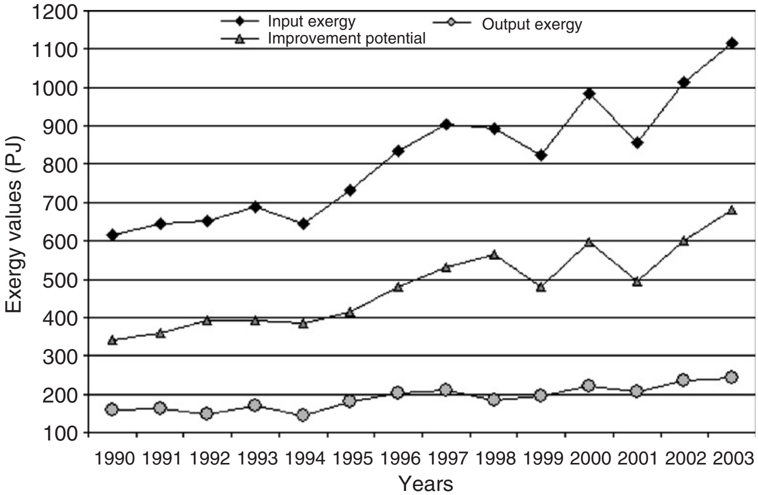

Fig. 5. Improvement potential of exergy utilization in the Turkish industrial sector over the period from 1990 to 2003.

6. Conclusions

The main conclusions drawn from the results of the present study may be summarized as follows:

(a) In the present study, whose methodology used is similar to that of Rosen and Dincer [8], who used Reistad's approach [12] with several minor differences, energy and exergy utilization in the TIS is reviewed and analyzed by considering the energy and exergy flows for the period 1990–2003. Energy and exergy analyses and hence efficiencies for the TIS are obtained, while energy and exergy analyses are performed in the TIS based on the actual data over the studied period.
(b) The overall energy and exergy efficiencies for the TIS are found to vary from 63.45% to 70.11%, and from 29.72% to 33.23% in the analyzed years, respectively.
(c) Energy and exergy efficiencies of the TIS are compared for the eight subsectors for 2003. The chemical and petrochemical subsector appears to be the most energy efficient sector, and the iron and steel subsector the most exergy-efficient one, due to the proper match of high temperature application with high quality energy resources.
(d) A comparison of the overall energy and exergy efficiencies of the TIS with the Saudi Arabia industrial sector is also presented for 2000 [10]. Although the sectoral coverage is different for each country, it is useful to illustrate how energy and exergy efficiencies vary. The TIS appears to be more efficient for that particular year.
(e) It seems that the current methodology is practical for analyzing energy and exergy utilization, which will help the Turkish industry in improving its energy savings through energy efficiency and energy conservation programs.
(f) It may be highlighted that exergy has been seen a key component for a sustainable society. Exergy analysis is a powerful tool, which has been successfully and effectively used in the design, simulation and performance evaluation of thermal systems as well as for estimating energy utilization efficiencies of countries or societies.

(g) The present study has clearly shown the necessity of the planned studies towards increasing exergy efficiencies in the sector studied. It also may be concluded that the analyses reported here will provide the investigators with knowledge about how much effective and efficient a country uses its natural resources. This knowledge is also needed for identifying energy efficiency and/or energy conservation opportunities as well as for dictating the energy strategies of a country or a society.

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